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# Structural design of linings

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ABSTRACT: The German Worksheet ATV-M 127-2 published in January 2000 after a seven years period of preparation and discussion is now well accepted in design practice for lining systems made of different materials and installed in various methods. The concept based on stress, deformation and stability analyses supports simple formula and diagram usage in standard cases like circular pipes up to ND 600 and more elaborate analyses for non-circular cross sections. Beside a short description of the design code the theoretical background is presented. Experimental test configurations are discussed regarding restrictions such as test specimen length, friction and load distribution. There is need of further research projects in co-operation with other universities to solve the problems left in theory and in practical use.

## 1 INTRODUCTION

Linings are used for trenchless rehabilitation of sewers or other pipe lines with growing importance for the infrastructural systems. The design of such structures has to deal with safety and useability aspects. As the transfer of loads from traffic, soil weight and water pressure to the lining is highly statical indeterminate a lot of research was necessary to get practicable results in the past decade. Soil is loading the host pipe and supports it simultaneously, as well known from structural analyses of buried pipes.

For a complete understanding the deteriorated host pipe (dp), the soil conditions (s) which are not well known in most practical cases and the liner (l) must be seen as an interacting and time depending system. In the past the following interactions have been investigated with more or less intensity:

1. Liners in a passive cavity (l system),
2. deteriorated pipe-soil system (dp-s system),
3. liner-deteriorated pipe-soil system (l-dp-s system).

Research started with the liner system as the clearest approach producing many helpful papers in the theoretical and experimental field, see references.

The dp-s system deserves more attention as it is the foundation of host pipe classifications which are necessary for liner design concepts.

For the l-dp-s system some Finite Element approaches are known, e.g. the host with four cracks. One of the questions still discussed is: are there any loads transmitted to the liner when a water table is absent? One position might be to regard traffic loads, soil movements or settlements and load redistributions caused by excavations near the rehabilitated pipe line as a *regular* case, another point of view is to restrict such possibilities to *special* investigations.

In Germany the design code ATV-M 127-2 appeared in January 2000 after a thorough research and discussion period. Decisions were necessary to create unique conditions and consequent design procedures applicable by the engineers of rehabilitation companies and understandable by pipe line experts. In the foreword of the Worksheet M 127-2 users are asked to report about their experience in usage.

The paper presented here is restricted to the liner and the dp-s system. However, some background information of the new design code (ATV-M 127-2) is given dealing with all systems mentioned above.

## 2 PRINCIPLES OF WORKSHEET ATV-M 127-2

### 2.1 *Symbols*

*Loading:*

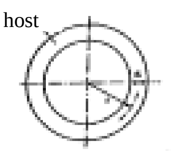
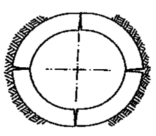
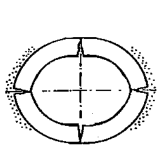
$h$ = soil cover above crown
$h_W$ = water table above invert
$q_v$ = vertical soil and traffic load above crown
$q_h$ = horizontal soil pressure
$p_a$ = external water pressure (with buoyancy)
crit $p_a$ = critical external water pressure (snap-through load)
$p_s$ = soil loads (host pipe state III)

$p_t$ = traffic loads (host pipe state III)
*Host pipe:*
φ = co-ordinate in circumferential direction
*r* = radius of middle axis
*s* = wall thickness
$S_R$ = pipe stiffness
*Soil:*
φ’ = angle of inner friction
$E_s$ = soil modulus near pipe springlines
$S_{Bh}$ = horizontal bedding stiffness of soil
*Lining:*
$r_L$ = radius of middle axis
$s_L$ = wall thickness
$E_L$ = Young’s modulus of elasticity
$\nu_L$ = Poisson ratio
$S_L$ = pipe stiffness of the liner
$\sigma_{bZ/bD}$ = bending tensile / pressure stress
$\sigma_u$ = ultimate stress
γ = safety factor
*Imperfections:*
$w_v$ = local imperfection
$\kappa_v$ = reduction factor for local imperfection
$2\varphi_1$ = opening angle of local imperfection
$w_{GR,v}$ = four-hinge global imperfection
$\kappa_{GR,v}$ = reduction factor for global imperfection
$w_s$ = annular gap width
$\kappa_s$ = reduction factor for annular gap
$\kappa$, $\kappa_{ijk}$ = reduction factor for combined imperfections
*Section forces and deformations:*
*N*, *n* = axial force, factor for axial force
*M*, *m* = bending moment, factor for bending moment
$\delta_v$ = vertical reduction of liner’s diameter in %

## 2.2 *Host pipe classification*

Classifying the host pipe state needs skills not only in rehabilitation methods but also in design aspects. In Worksheet ATV-M 127-2 several decisions are necessary before structural analysis is possible.

Table 1. standard cases (damage picture is constant along the pipe’s axis, two dimensional load behavior)

| | host pipe state definition | damage picture | relevant loadings |
|---|---|---|---|
| I | host pipe‘s structure is safe, but leaking, no cracks except cracks from shrinkage |   | water table $p_a$ minimum: $h_W$ = 1,5 m or $h_W$ = *OD* + 0,1 m above liner invert (circular and non-circular linings) |
| II | host pipe-soil system is safe, four longitudinal cracks, deformations less than 5 % of diameter |  | |
| III | host pipe-soil system not safe for long-term conditions, four longitudinal cracks, deformations bigger than 5 % of diameter |  | water table like host pipe states I and II, soil / traffic loads $p_s$ / $p_t$ |

A very important part of the work is to determinate the host pipe state. The design group decided to restrict to three cases which are most relevant and safe regarding possible damages in sewers. Table 1 contains the main visual criteria for states I, II and III; all of them regard the host as not totally broken and the safety factor being obviously greater than 1,0 at the time of inspection.

Local damages such as transverse cracks or small holes in the pipe’s wall may not effect the structural system in such a way as longitudinal cracks will do. Lateral connections lined by a short liner and connected to the main liner will stiffen the system if a shear bond is achieved.

## 2.3 *Deteriorated pipe-soil system (dp-s system)*

For determination of limit loads of the dp-s system (sewer with four longitudinal cracks) the following assumptions are valid:

- constant vertical and horizontal pressures $q_v$ and $q_h$ caused by soil and traffic loads, see figure 1,
- triangular bedding reaction distribution,
- linear spring behavior (Winkler’s law),
- equilibrium equations defined for the deformed system,
- eccentric hinges simulating the contact regions of the pipe’s quarters in longitudinal direction,
- limiting bedding reactions by 75 % of the passive soil pressure.

The equations are solved for different amplitudes of the global imperfection and drawn as load-deflection curves in figure 2. To the maximum load parameter $q_v$ / $S_{Bh}$ (where $S_{Bh} = 0{,}6 \times E_s$ is the horizontal stiffness as defined in ATV-M 127-2 belong deflections from about 15 % to 20 % of the pipe’s nominal diameter. Dividing the maximum load by the safety factor γ = 2,0 deformations of about 5 % to 6 % result.

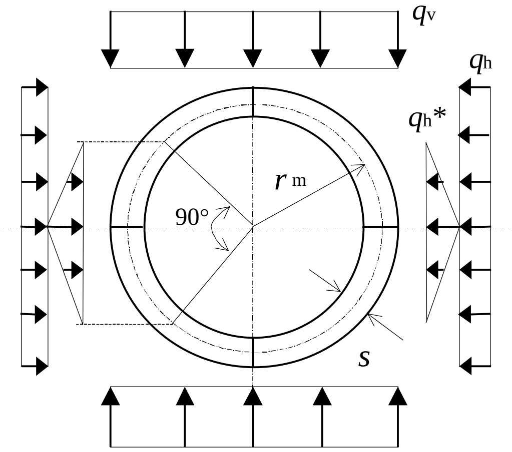



Figure 1. Model of the deteriorated pipe-soil system (dp-s) with four cracks in crown, springlines and invert, vertical and horizontal loads $q_v$ and $q_h$, bedding reactions $q_h$*

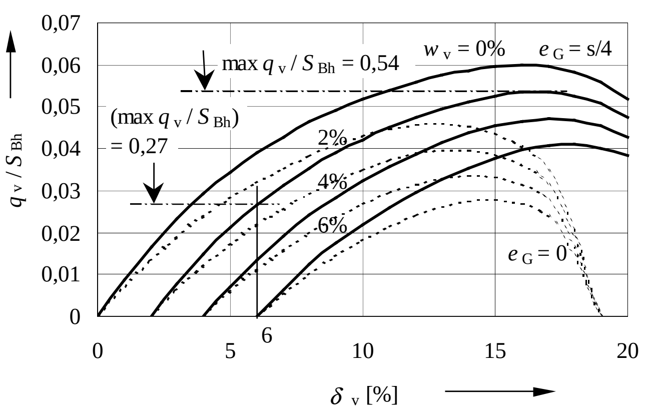



Figure 2. Load-deflection curves for the deteriorated pipe-soil system (dp-s system) evaluated by the model in figure 1, soil with angle of inner friction φ' = 30°, eccentricity of the hinges $e_G = 0$ and $e_G = s / 4$

Thus a distinction between host pipe II and III might be possible if deformations exceed a limit of say 5 %, see table 1. Additional criteria can or must be regarded however, e.g. observations of time dependency of host pipe's deformations and field tests of soil properties $E_s$, φ' and compaction at the pipe's springlines.

## 3 THEORETICAL ASPECTS

### 3.1 *General assumptions*

For investigations of the liner system basic assumptions are made (Falter 1991):

1. Geometry and loads are constant in longitudinal direction of the pipeline. Thus the three dimensional problem is reduced to one or two dimensional.
2. Friction between host pipe and liner is neglected.
3. Host pipe and lining are not bonded so only contact pressure is present. Bonded lining systems are less relevant in practice and need separate investigations.
4. The host pipe is not water tight. Thus the water pressure is acting at the outer surface of the lining as a non conservative loading.

These assumptions are describing correctly the liner problem and accepted in most lining research papers. They are used as a fundament for the following studies again.

It must be emphasized that in experimental work it is not possible to adjust all test conditions to these assumptions (caused e.g. by end restrictions and different pressure distribution) leading sometimes to misinterpretations when results are compared.

### 3.2 *Imperfections*

#### 3.2.1 *Circular linings*

The buckling loads of circular linings in a rigid cavity are well known by theoretical research (e.g. Glock 1977) and proved by experiments (e.g. Link 1987).

These approaches primarily used for water supply pipes and shaft linings seemed to be applicable on sewer linings as well but imperfections had to be introduced simulating the rough situation in deteriorated sewers. The imperfections had to be primarily classified under safety and then economical aspects.

Variations of imperfections seemed to be possible in

- shape functions,
- distribution in longitudinal direction,
- distribution in circumferential direction,
- amplitudes.

generating a lot of parameters. Further research had to decrease the number of parameters to improve practical use: not every special sewer damage should produce a special design procedure.

The result can be summarized as follows. Three imperfection functions proved to be relevant for linings

- imperfection 1 as a local imperfection distributed over a part of the circumference,
- imperfection 2 as a global imperfection distributed over the whole circumference,
- imperfection 3 as an annular gap.

The distribution in longitudinal direction had to be set constant which proved to be the most unfavorable possibility.

The distribution of the imperfections in circumferential direction (figure 3) is defined for

- imperfection 1: restricted by an angle $2\varphi_1$ where this angle must be evaluated by a minimization procedure of the critical pressure,
- imperfection 2: following the shape of the host pipe's deflection after being cracked four times in longitudinal direction,
- imperfection 3: a constant distance between lining and host pipe.

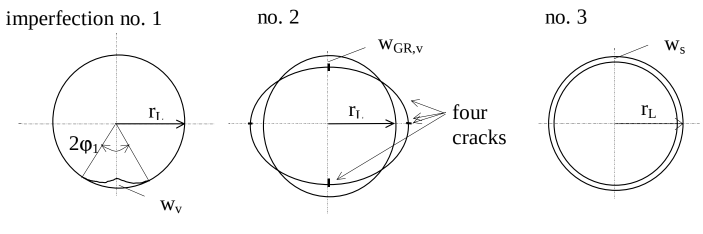



Figure 3. Imperfections no. 1, 2 and 3 as defined in Worksheet ATV-M 127-2: local and global imperfection, annular gap

The imperfection amplitudes $w_i$ have significant influence on the economical and safe dimensioning of the lining structures. For reasons of competition in the rehabilitation market strict regulations are necessary.

The amplitude of local imperfections $w_v$ has often been discussed in practice and literature (e.g. Boot

1998 & Artillan 2000). Imperfection no. 1 alone is similar to the relevant buckling mode. In modern structural analyses (Pflüger 1964) and design codes (e.g. EC 3) any imperfection function approximate to the buckling mode is to apply for determination of the lowest critical loading. So for reasons of safety in all analyses that include stability problems a sufficient amount of local imperfections like form 1 or similar to it has to be added to the geometry. This is of great importance specially if video inspections show imperfections of type no. 2 alone.

Imperfection no. 1 must be applied not only for theoretical purposes but for practical aspects as well. Sewer sediments which cannot be removed, linings that flatten during installation or even get folds in longitudinal direction are a realistic scenario and must be taken into account. Other effects are variations in wall thickness and material discontinuity.

Any possible but realistic case had to be considered before the presentation of the German Worksheet M 127-2 for practical use. After an intensive discussion between contractors, municipalities and the design group the values in table 2 were finally prescribed for analysis.

Table 2. Amplitudes for imperfections due to the German Worksheet ATV-M 127-2

| imper-fection | CIPP-liners | deformed and re-deformed liners |
|---|---|---|
| 1. $w_v$ | 0,5 % + 1,5 % *) = 2 % | |
| 2. $w_{GR,v}$ | host pipe state I: 0; states II + III: ≥ 3 % | |
| 3. $w_s$ | 0,5 % | 2 % |

*) structural and geometrical imperfections; the geometrical part of 1,5 % may be reduced to 0,5% if exact measurements are present (sum ≥ 1 %).

Thus the critical loads of imperfect liners can be determined by the following modified Glock equation:

$$crit\ p_a \cong \kappa \cdot \alpha_D \cdot S_L \quad (1)$$

where $\kappa \cong \kappa_v \cdot \kappa_{GR,v} \cdot \kappa_s$ = reduction factor for combined imperfections due to ATV-M 127-2;
$\alpha_D = 2{,}62 \cdot (r_L / s_L)^{0{,}8}$ = snap-through factor;
$S_L = (EI)_L / r_L^3$ and $I_L = s_L^3 / 12$ for homogeneous liner walls.

### 3.2.2 *Non-circular linings*

Cross sections like egg shapes with three, four or even five radius' are familiar in German sewer systems specially in bigger towns. Egg shaped sewers possess regions of less curvature beneath the springline where buckling happens if water pressure is present.

For circular linings the buckle starts at the invert, for egg shaped liners it will begin at the flat region (figure 4a) or at the opposite side or possibly simultaneously. In (Falter 1997b) systematic calculations and plots are presented to demonstrate the buckling behavior under the assumption of the most unfavorable conditions listed in chapter 3.1.

Figure 4 shows one and two mode buckling depending on the amplitude of the local imperfection. The host pipe and liner parameters are

- $B$ / $H$ = 800 / 1200 mm (*normal egg*),
- wall thickness $s_L$ = 25 mm,
- longterm modulus of elasticity $E_L$ = 1800 N/mm²
- local imperfection amplitudes 0, 0,1 %, 0,5 % and 1 % of the maximum radius (0, 1, 6 and 12 mm)
- opening angle $2\varphi_1$ = 35° (e.g. approximately the total width of the region with less curvature),
- no annular gap width.

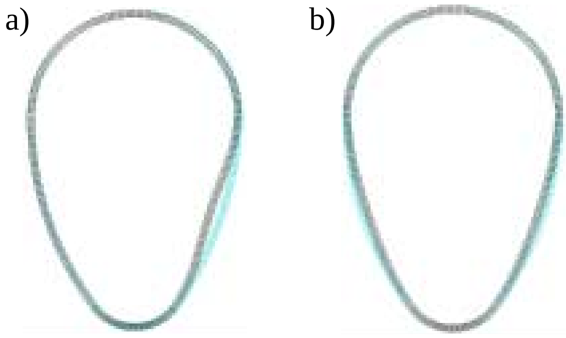



Figure 4. One and two mode buckling of an egg shaped liner, to be used as local imperfection distribution

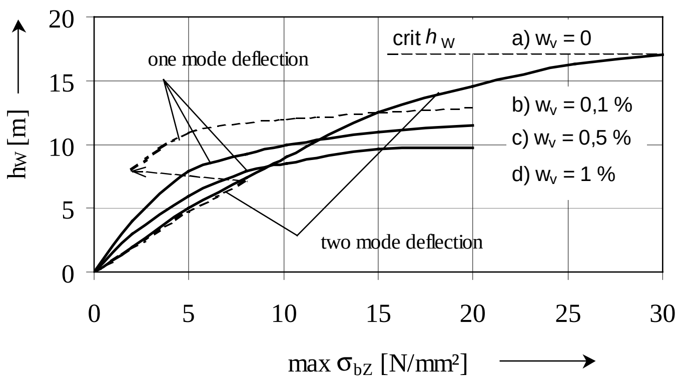



Figure 5. Loading versus tensile stress plot for egg shaped liners with one mode local imperfections and varying local amplitudes (Falter 1997a)

In figure 5 tension stress $\sigma_{bZ}$ in the middle of the flat region is drawn at the horizontal axis and the water table $h_W$ at the vertical axis.

Line a is growing continuously until crit $h_W \cong$ 17 m. Line b shows a paradox behavior; initially it follows line a (free of imperfection); at a special water table it suddenly changes to smaller stresses but increases again with a steep slope and becomes infinite at the critical water table crit $h_W \cong$ 13,5 m. The curves c and d for bigger amplitudes of $w_v$ increase like curve a but at the beginning curves c and d show lower stresses than curve a. At about 10 m water table the stresses exceed curve a.

The following results are important for the development of safe design criteria:

1. Neglecting local imperfections (no. 1: $w_v$) leads always to a two mode buckling shape with unsafe critical loads.
2. Applying local imperfections (no. 1) with a very small amplitude leads correctly to a one mode buckling shape but less tension stress then case 1.
3. An appropriate imperfection amplitude is found to be at least 0,5 % to 1 % of the maximum radius, see ATV-M 127-2.
4. The annular gap (no. 3: $w_s$) caused by shrinking of the liner material has to be added to the system.

Global imperfections caused by deformations of a cracked host pipe (imperfection no. 2: $w_{GR,v}$) can be treated as follows:

1. calculate the *egg shaped lining* with imperfections no. 1 and no. 3,
2. calculate a *circular lining* with the crown radius of the egg shape and *all* relevant imperfections together (imperfections no. 1, 2 and 3).

This recommendation can be explained as follows: Global and local imperfections are not interacting as they are positioned at different places on the liner's circumference and their negative influence on the critical load is separated by this. Note that for circular linings flattening by imperfection no. 1 and no. 2 has the same position in the invert but for egg shaped liners the crown is critical for the global imperfection (no. 3) and the flat region is critical for the local imperfection (no. 1).

The discussion for non-circular linings is not finished until now. For this reason some advice is given in the German Worksheet ATV-M 127-2 helping to accomplish computer solutions; however no diagrams ready to use are available yet.

### 3.3 *One and two dimensional modeling*

The system for the structural analysis of linings is the cylinder encased in a rigid boundary and subjected to water pressure at the interface between liner pipe and host pipe. The bending stiffness parameter *EI* of the liner is small because of the specific properties of the plastic material and the wall thickness. Large compressive forces can cause stability failure observed as a snap-through phenomenon in testing arrangements but in installation faults as well, e.g. if excessive grout pressure is applied to fill the annular gap.

At least three different analytical and numerical models to describe the complete non linear behavior of liner stresses, deflections and buckling have been developed:

*Model 1* is the exact curved beam formulation for one side bedded rings. In such cases equilibrium of the section forces and the applied pressure has to be formulated by use of the deformed geometry (figure 6a). As a completely analytical approach a non linear system of differential equations describes the constitutive and equilibrium conditions.

$$
\begin{aligned}
\xi^{\cdot} &= \eta + (1+\varepsilon)\cos\psi - 1 \\
\eta^{\cdot} &= -\xi + (1+\varepsilon)\sin\psi \\
\psi^{\cdot} &= n + \xi \cdot m \\
n^{\cdot} &= q \cdot (1+\psi^{\cdot}) \\
q^{\cdot} &= -n \cdot (1+\psi^{\cdot}) - k \cdot \alpha + k \cdot \beta \cdot \eta \\
m^{\cdot} &= -q \cdot (1+\varepsilon)
\end{aligned}
\qquad (2a\text{-}f)
$$

where $\alpha = p_0 \cdot r^3 / EI$ (load parameter), $ß = c \cdot r_L^4 / EI$ ($c$ = bedding modulus), $\zeta = v / r_L$ ($v$ = tangential displacement), $\eta = w / r_L$ ($w$ = radial displacement), $\psi$ (rotation), $n = N / EA$ (axial force), $q = Q / EA$ (shear force), $m = M / (E \cdot A \cdot r_L)$ (bending moment), $\varepsilon = n + m$ (strain), $k = I / (A \cdot r_L^2)$ (parameter), $...^{\cdot} = d... / d\varphi$ (differentiation operator, $\varphi$ = co-ordinate in circumferential direction).

Using very stiff beddings ($ß > 10^4$) solutions for liners are gained by a modified Newton Raphson method and presented as load-deflection curves in (Falter 1980 & 2000), see figure 6a.

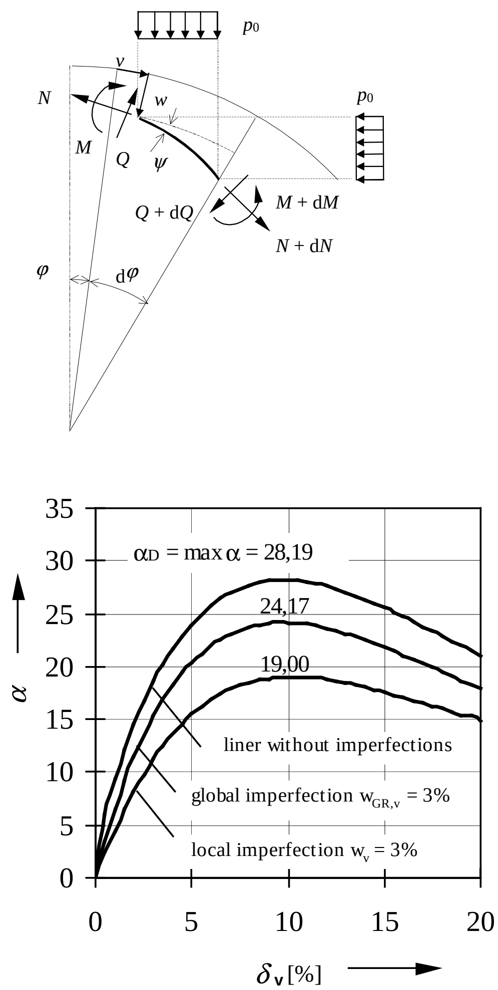



Figure 6a. Model 1, section forces and loading of deformed element; deflections of liner versus water pressure parameter α (host pipe states I and II, l system)

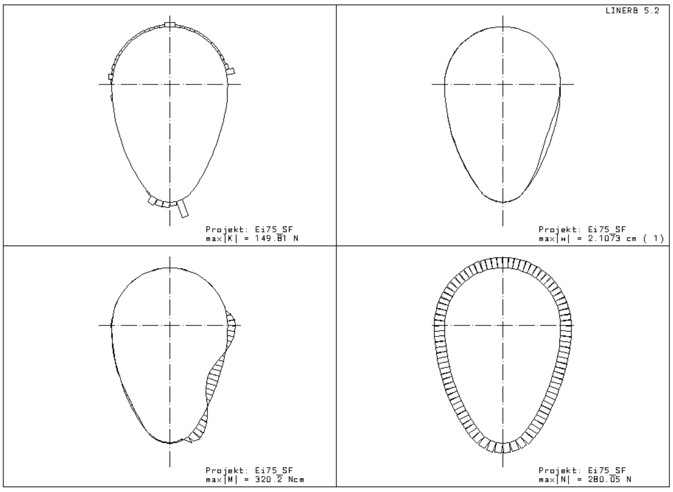



Figure 6b. Model 2, straight beam model for the evaluation of contact width, deflections and section forces

*Model 2*: In the early 90$^{th}$ a simple finite model based on straight beam elements was developed in order to derive diagrams for the engineer's use. The approximation of any geometry by a polygone is usually a stiffer system when compared with curved beam solutions like model 1. For this reason the Poisson ratio was neglected in ATV-M 127-2 for an adequate reduction of the liner stiffness.

An example for an egg shaped liner is shown in figure 6b – in the first picture the width of the contact region is the zone free of contact forces. The flexibility of this model for all analyses is demonstrated by the pictures of deflection, bending moment and axial force.

*Model 3* is a Finite Element description with rectangular elements for plain strain conditions. This model had to be developed for solutions of host state III at first (Falter 1996) but it proved to be very useful for exactness checks in host pipe states I and II as well.

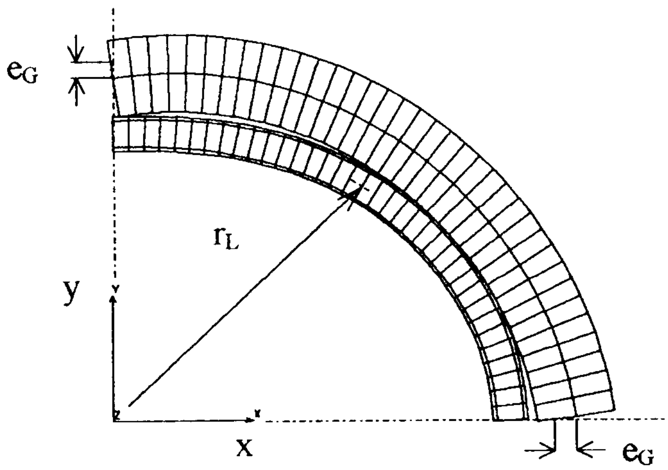



Figure 6c. Model 3, deflections of liner and host pipe subject to soil and traffic loads (host pipe state III, l-dp-s system)

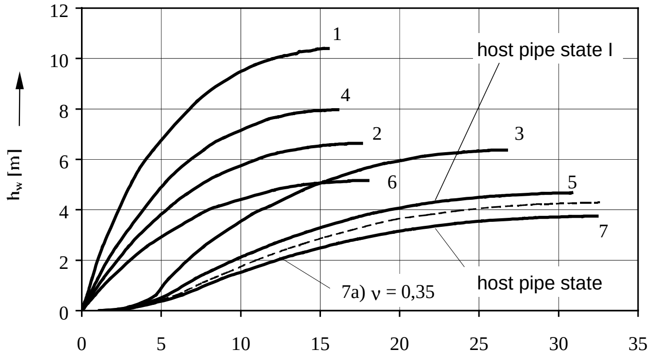



Figure 7. Model 3 load-deflection curves for circular lining without (1) and with imperfections: 2) $w_v$ = 2 %, 3) $w_s$ = 0,5 %, 4) $w_{GR,v}$ = 3 %, 5) $w_v + w_s$, 6) $w_v + w_{GR,v}$, 7) $w_v + w_s + w_{GR,v}$

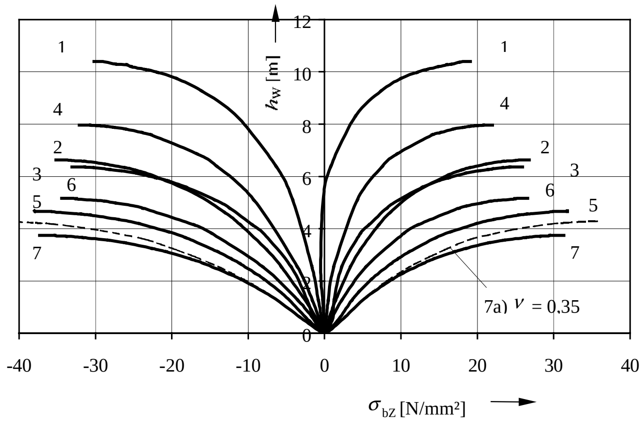



Figure 8. Model 3 stress curves for circular lining without (1) and with imperfections (for 2 – 7 see figure 7)

## 3.4 *Exactness of solutions*

### 3.4.1 *Circular linings*

Figures 7 and 8 show the load-deflection curves and the development of maximum tension and pressure stress in the wall of a circular liner. The parameters of the numerical example are

- Nominal diameter ND 600,
- Young's modulus of elasticity $E_L$ = 1800 N/mm²,
- wall thickness $s_L$ = 7 mm (3 elements in radial direction),
- imperfections as prescribed in ATV-M 127-2, see table 2.

For the example chosen here which is representative for cured-in-place-pipe (CIPP) the following main results of models 2 and 3 are obvious from figure 7:

- The critical water table is significantly reduced by all kinds of imperfections; simultaneously stresses increase.
- The reduction factors κ of the critical loading for local and global imperfections (no. 1 and 2) are very close between all models, see table 3, rows 2 and 4; similar results of model 1 in (Falter 2000).

- For the annular gap the reduction is underestimated by model 2 in a range of about 9 %, see table 3, row 3. More detailed results will be presented in another paper.
- The combination of different imperfections can be safely described by multiplication of the reduction factors due to single imperfections, see table 3, rows 5, 6 and 7.

Table 3. Reduction factors for imperfections evaluated by model 2 and 3 ($\nu_L = 0$, exception row 7a: $\nu_L = 0{,}35$)

| | $w_v$ | $w_s$ | $w_{GR,v}$ | crit $h_W$ model 2 | crit $h_W$ model 3 | κ model 2 | κ model 3 | $\Pi\,\kappa_i$ |
|---|---|---|---|---|---|---|---|---|
| | % | % | % | m | m | - | - | - |
| 1 | 0 | 0 | 0 | 11,90 | 10,40 | 1 | 1 | - |
| 2 | 2 | 0 | 0 | 7,55 | 6,64 | 0,636 | 0,638 | - |
| 3 | 0 | 0,5 | 0 | 7,97 | 6,37 | 0,671 | 0,612 | - |
| 4 | 0 | 0 | 3 | 9,12 | 7,97 | 0,768 | 0,766 | - |
| 5 | 2 | 0,5 | 0 | 5,69 | 4,68 | 0,479 | 0,450 | 0,390 |
| 6 | 2 | 0 | 3 | 5,85 | 5,17 | 0,493 | 0,497 | 0,489 |
| 7 | 2 | 0,5 | 3 | 4,56 | 3,75 | 0,384 | 0,361 | 0,299 |
| 7a | 2 | 0,5 | 3 | 5,13 | 4,29 | - | - | - |

The reduction factors $\kappa$ in table 3 are evaluated by

$$\kappa = \frac{\text{crit } h_W (w_i > 0)}{\text{crit } h_W (w_i = 0)} \tag{2}$$

where $w_i = w_v$, $w_{GR,v}$, $w_s$ or combinations.

The approximate multiplication $\Pi\kappa_i$ for combined imperfections overestimates reductions by about 15 %. In ATV-M 127-2 only tables for single imperfections are drawn to be combined by multiplication. The German design code allows to create special reduction factors $\kappa_{ijk}$ for combined imperfections if necessary.

### 3.4.2 *Non-circular linings*

Comparisons of results for egg shaped linings are more complicate because stresses in the wall may spread in a wide range (see figure 5) and experimental data are not available yet.

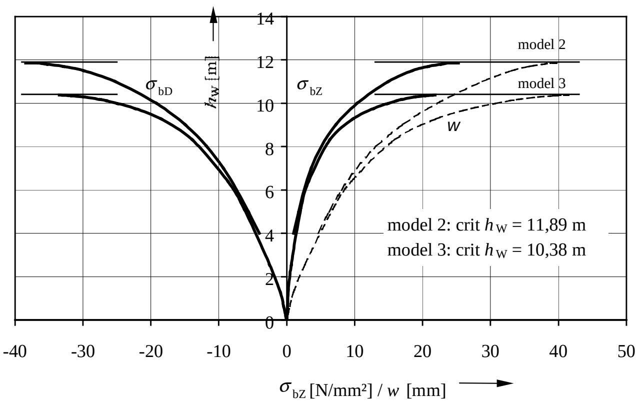



Figure 9. Load-deflection curves for an egg shaped liner with imperfections $w_v = 0{,}5$ % of maximum radius and $w_s = 0$ (models 2 and 3, $\nu_L = 0$)

Figure 9 shows the deflections and the maximum stresses in the mid of the region with less curvature versus the water table $h_W$. The critical water table is reached when deflections and stresses converge to a horizontal line.

If a local imperfection is applied with a sufficient amplitude the resulting deflection curve is not symmetric (figures 4a and 6b). As pressure stresses exceed tension more than two times appropriate liner material tests are necessary. The curves for model 2 (straight beams) and model 3 (COSMOS/M) are close together except for a water table near to failure. Model 2 overestimates crit $h_W$ by about 14 % already mentioned for circular linings in chapter 3.4.1.

## 3.5 *Buckling load or stress dimensioning?*

All load-stress curves presented (figures 5, 8 and 9) show the same principal behavior: Stresses grow continuously and non linearly with increasing loads and get infinite at the critical water table. As a rational design criterion the following limitations are possible

$$h_W \le \frac{\text{crit } h_W}{\gamma_F} \tag{3a}$$

$$\sigma_{hw,u} \le \frac{\sigma_u}{\gamma_M} \tag{3b}$$

where $h_{W,u} = \gamma_F \cdot h_W$ = design load for water table; $\gamma_F$, $\gamma_M$ = appropriate partial safety factors for forces and material.

As the ultimate loads of figures 7 and 8 are obviously equal equation (3b) leads to lower water tables. The difference is small in cases of sufficient values for $\sigma_u$ but may be big in other cases (e.g. Trolining).

Note that formula (3b) includes stability analysis *and* stress proof (tension or pressure stress if necessary) as well. If non linear stress curves are available no additional stability check is necessary (EC 3). This is valid if no bifurcation phenomenon arises before snap through, but this had not been observed in liner testing and theory so long.

The appendix of M 127-2 contains elaborate tables for section force factors n and m to determine $\sigma_{hw,u}$ in equation (3b) for all host pipe states in table 1.

## 3.6 *Three dimensional modeling*

Despite the general assumptions as described in chapter 3.2 in some cases the three dimensional problem cannot be reduced to two dimensions. Such problems arise e.g. in testing configurations, presence of concentrated loads, for local damage investigations and side connections.

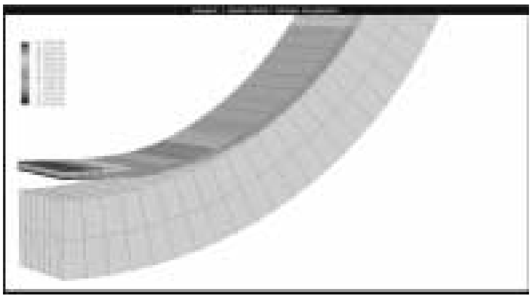


Figure 10. Deformed 3D-structure with stresses in circum-ferential direction

Figure 10 shows an extension of the 2D model in longitudinal direction for investigations of restritions by clamped ends in liner testing. The numerical calculations are performed by the FE-package (ABAQUS). 3D models are also helpful for the evaluation of the ASSUR test box results, see chapter 5.

## 4 PRACTICAL QUESTIONS OF ACTUAL INTEREST

### 4.1 *Field observations, damage definitions and practical decisions*

All attempts to create models for liner analyses have to refer to real situations as found in deteriorated sewers. Assumptions of small imperfections may be inconsistent with severe corrosions in sewers like figure 11. It is obvious that thin walled close fit liners are not able to span all irregularities of geometry and holes (figure 12) without reduction of stability belonging to it.

Another question of practical interest is the circumferential bearing integrity of the pipeline which is a *condition for all host pipe states* defined in table 1. In figure 13 corrosion affects the whole wall thickness and it cannot be excluded thus circumferential forces are transferred by the host no longer. Such case is clearly to be seen in figure 14 where parts of the invert have fallen down. If replacement of the pipe is not possible and a non trenching solution must be chosen the installation of stainless steel collar before lining could improve host state III.

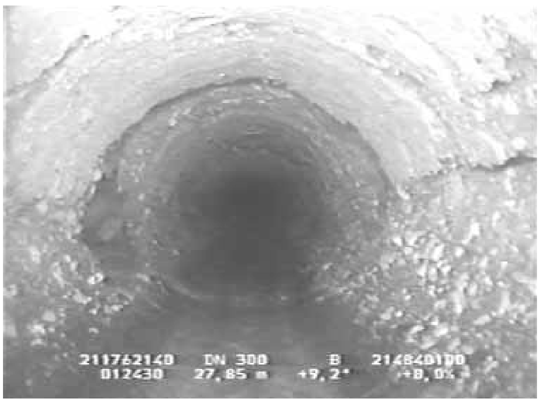



Figure 11. Concrete corrosion

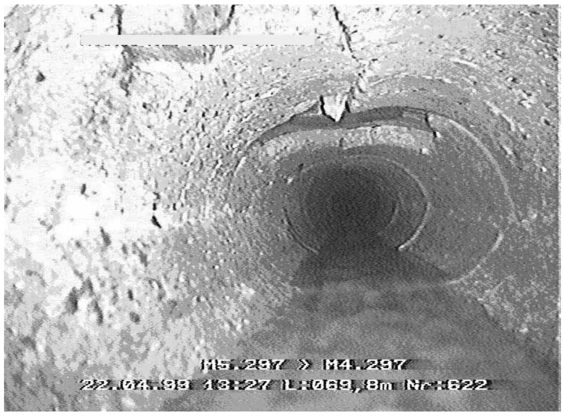



Figure 12. Cracked pipe with holes

Figure 13. Invert gap

Figure 14. Parts of the invert missing

### 4.2 *Faults in rehabilitation*

Figure 15. Transverse folds in re-deformed lining

Faults in rehabilitation may give good informations valuable for progress in lining methods. In (John & Lenz 1998) many examples and suggestions to avoid faults are summarized.

It is obvious that careful calculations at the beginning of the rehabilitation work are substantial to prevent liner failure in installation and usage.

In some practical situations it is very expensive if liners have to be cut and pulled out of the sewer again. So decisions are necessary about the structural safety of installations that are not exact close fit like figure 15. The design concept presented here is also capable to give answers to such cases.

## 5 ASSUR PROJECT

In the year 1999 the project 01 RA 9803/8 *„Abwasserkanäle und -leitungen, Statik bei der Substanzerhaltung und Renovierung“ ASSUR (Sewers – structural analysis for preservation and renovation)* was started by the Universities of Applied Sciences in Bremen and Münster together with other cooperative partners. The research is sponsored by the German Ministry of Education and Research (BMB+F).

The following aims are to be worked out until end of 2001 (Steffens et.al. 2001):

a) Development, construction and testing of a testing vehicle BELFA for bridges and sewers as well,
b) development of a mobile measurement technique in non-accessible sewers,
c) basic tests for statics and deformation measuring in a test box (figure 16),
d) testing with pilot projects,
e) development of recommendations and standards.

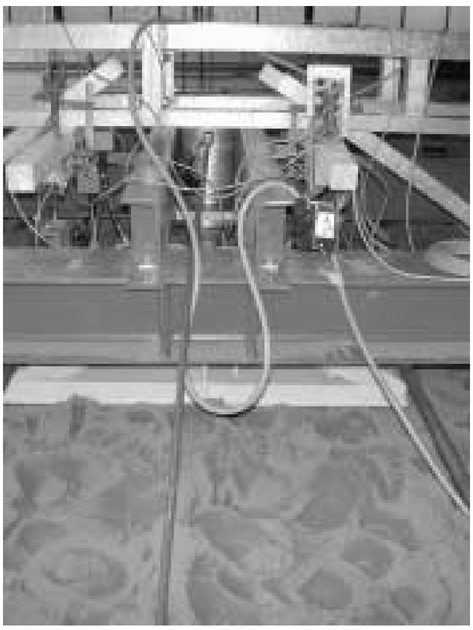


Figure 16. Box loading test for the project ASSUR with hydraulic pressure units and measurement equipment

Several box loading tests are under work measuring soil pressure, soil settlements and pipe deformations due to a concentrated surface load. The evaluation is accomplished by a three dimensional Finite Element model (ABAQUS).

The parameters of box geometry have been varied carefully and proved to guarantee absence of bridging effects in the box. One result is: the pressure at the pipe's surface is significantly higher than predicted by the formulas of design codes.

## 6 CONCLUSION, FUTURE RESEARCH

In the year 2000 the German Worksheet for liner design (ATV-M 127-2) appeared and practical experience is available now. This paper is dealing with parts of the worksheet, e.g. the deteriorated pipe-soil system (dp-s system), host pipe states I and II (l system), the importance of imperfections, their combinations and special problems of egg shaped linings.

Additional research on the exactness of the critical water table generated by different models show acceptable correspondence for a standard cured-in-place-pipe with small and moderate imperfections. However some systematic calculations are still necessary to optimize safe structures.

With the topical ASSUR project performed in Bremen and Münster new experiences are expected in modeling and field testing.

## 7 ACKNOWLEDGEMENTS

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